Renewable and Sustainable Energy Reviews 16 (2012) 5443–5450

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Parameters influencing the design of photobioreactor for the growth of microalgae

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A R T I C L E I N F O

Article history:
Received 27 December 2011
Received in revised form
29 May 2012
Accepted 4 June 2012
Available online 10 July 2012

Keywords:
Carbon dioxide sequestration
Biofixation
Microalgae
Photosynthesis
Autocatalysis
Photobioreactor

A B S T R A C T

Carbon dioxide sequestration using microalgae is the most promising method for combating global warming. Growth of microalgae is influenced by the availability of carbon dioxide, number of photons, initial concentration of microalgae and nutrients. The transfer of carbon dioxide from flue gas and absorption of photons from sunlight are influenced by the surface area/volume ratio of photobioreactor. The growth rate of microalgae follows lag, log, deceleration and stationary phases. The rate of growth increases with concentration of microalgae till an optimum concentration of algae is reached and then decreases for any fixed operating conditions and selected microalgae. At an optimum concentration the rate is the highest always. Operating a photobioreactor at this optimum concentration with highest surface area to volume ratio would require the smallest size of photobioreactor for a given production rate. Based on the review on the performance of various existing photobioreactors and the growth mechanism of microalgae it is observed that the design and operation of an efficient photo bioreactor system should consider (1) providing highest spread area to volume ratio (2) maintaining optimum concentration matching the highest rate (3) harvesting the excess microalgae formed over the optimum concentration to maintain the optimum concentration and (4) adding nutrients to the growth medium to maintain nutrient concentration at a constant level.

Contents

1. Introduction

Flue gases from thermal power plant are responsible for more than 7% of the total world Carbon dioxide (CO_2) emissions [1]. Due to GDP growth, India's electricity consumption was increased by 75% over the past ten years and coal demand has risen by 50% [2].

Coal is the most polluting fuel in terms of greenhouse gases and accounts for the highest CO_2 emissions. In addition, coal having high ash content (15–45%) and low calorific value requires additional infrastructure for coal cleaning and also causes environmental risk. During coal combustion, it releases respirable

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http://dx.doi.org/10.1016/j.rser.2012.06.013

particles, noxious gases, toxic trace elements, and radioactive particles into the atmosphere. The health problems due to burning of coal are cancer, bone deformation, black lung, sterilization, and kidney diseases. Inspite of these problems, coal is still used as a fuel in developing countries since it is the only source available meeting out the required energy demand. Generally the power plant efficiency in India varies from 27% to 32%. The power generation through coal burning emits 0.8–1.2 kg of CO_2/unit of electricity generated releasing flue gas of 10–15% CO_2 [3]. It is predicted that CO_2 levels above 450 ppm in the atmosphere will have severe impacts on sea levels, global climate patterns and survival of many species and organism [4]. To maintain the CO_2 level within the safe limits in the atmosphere, either the emission has to be reduced or it has to be treated.

Many countries (developing and developed) are targeted to reduce the green house gas emission. India's carbon reduction target is 20–25% compared to the 2005 (Copenhagen record). Cleaner technologies are also helpful to substantially reduce the CO_2 emission. Further structural reforms in the plant will lead to appreciable CO_2 abatement per kW h and the theoretical efficiency is estimated to be 38% [5–7]. However, if these options were aggressively pursued, at best, this effort would only reduce emissions from coal by 10–20% [8]. The pre combustion and oxy fuel combustion capture technologies can be applied to the newer power plants. Retrofitting the available coal plants with integrated gasification and combined cycle (IGCC) will still add cost to it [9]. Even though several attempts are made to increase the efficiency thereby reducing the CO_2 emission, the problems associated with emitted CO_2 still exists. Separation of oxygen from air is quite uneconomical for oxy fuel combustion and carbon capture and storage (CCS) will add further cost [10,11]. Hence mitigation of CO_2 by other post combustion capture technologies needs to be analyzed. To choose the best mitigation technology for CO_2 with reference to technical, economical and environmental aspects, an analysis is required to review the available methods of CO_2 sequestration.

Current technologies for sequestration of CO_2 can be divided in to three groups namely (1) Carbon Capture, Storage and Utilization (2) Fixation.

1.1. Carbon capture, storage and utilization

The first step is the capture of CO_2 from the flue gas. The most widely used method for capturing of CO_2 is scrubbing by mono ethanol amine [3]. Other technologies include (a) molecular sieve technology [12,13] as well as (b) desiccant adsorption [14]. Incorporation of capture and compression system to power plants leads to drop of thermal efficiency from 38.5% to 29.3% and subsequently increases the coal demand further add capital cost to the system [3]. With today's technologies, the incremental cost of applying carbon capture and storage by means of chemical absorption to new conventional coal and gas plants is about \$225/tC to \$230/tC, but near-term technical improvements (i.e., 2012 technology) could reduce these costs to about \$160/tC to \$190/tC [10]. Previously the captured CO_2 was stored under Deep Ocean [15], surface [16] and underground geological cavity. However the development of efficient pumping methods, uncertainties in the long term stability of the stored CO_2, possible severe negative impact on environment and high capital and energy cost offer major challenges in storing [16,17]. The combined costs of transport and storage are typically estimated to range from about \$20/tC to \$55/tC stored and transport costs are estimated to be about \$5/tC to \$10/tC per 100 km [8]. Anderson and Newell [18] detailed and estimated the cost of CCS of various storage technologies and also CO_2 avoided cost due to the integration of CCS to the power plants.

Captured and stored CO_2 could be used commercially, as feedstock for manufacturing chemicals. This offers the twin benefits of sequestration of the gas as well as replacing other manufactured feed stocks. It is already used for a wide range of purposes in the food and oil industries although, in most cases, the gas is not permanently stored in the products but is quickly lost to the atmosphere. CO_2 utilization options enhance oil recovery, coal bed methane recovery and fertilizer plants. The estimated cost of capturing and transporting to an oil field on a daily basis of 1200 t of CO_2 is approximately \$110 million [2]. This clearly indicates an additional investment without much return. Inspite of this poor economics, ever increasing demand for power leads to further generation of CO_2 and release into the atmosphere.

1.2. Fixation

The natural sinks for CO_2 are terrestrial vegetation, soil as well as the oceans [16]. The methods for increasing the rate of CO_2 sequestration through enhancement of natural sinks are (i) afforestration [19], (ii) ocean fertilization, (iii) rock weathering enhancement (iv) microalgae culture in photobioreactors and (v) artificial photosynthesis. The CO_2 consumption rate by trees and microbes varies with type and location. Every year, carbon dioxide fixation rate by natural sinks was estimated to be 50–100 Gt [16] by oceans microbes, whereas terrestrial vegetation ranges from 5 Gt-C to 10 Gt-C [20].

The carbon uptake rate of microalgae was 25.6 kg C/m^3/year [21] and 0.3–0.9 kg C/m^3/ year for trees [20,22]. The water requirement for fixing 1 kg of CO_2 by microalgae was 140–200 kg and it was more than 550 kg for trees [20]. Waste waters and high saline water unsuitable for agriculture use or human consumption can be used to grow microalgae [20]. In addition, flue gas can be directly used for microalgae growth since SOx and NOx in the flue gas helps in increased growth rate [23]. Microalgae have higher theoretical photosynthetic efficiency (9%) than higher plants (6%), though in practice the values are still lower [24–33]. Hence Biosequestration of CO_2 by microalgae is a promising technology. It is a permanent, reliable solution for CO_2 [34–42] rather than a temporary, unsafe solution like capture or storage methods. Hence in this paper detailed analysis is done to review the parameters affecting the growth of microalgae, design of photobioreactors used, to suggest new type of reactor and operating conditions.

2. Mechanism of algae growth

The essential requirements for microalgae growth are the carbon dioxide, light, nutrients and microalgae concentration.

2.1. CO_2

Utilization of CO_2 by microalgae for its growth takes place by two stages: absorption of CO_2 from flue gas by mass transfer/ chemical reaction and fixation of CO_2 by photosynthesis.

2.1.1. Absorption of CO_2

Absorption of CO_2 for microalgae growth could be done in water and alkaline solution.

Absorption of CO_2 from flue gas to microalgae in water is a key factor in cultivating photosynthetic microorganism. This is due to low solubility of CO_2 in water [43]. The solubility of CO_2 in water is generally very low i.e., 1650 ppm at 25 °C in pure water. The pH decreases with increase in solubility representing carbonic acid formation. The CO_2 in water will be present in four different

forms: CO_2 (pH < 5), CO_3^{2-}(5 < pH < 7) bicarbonate forms (7 < pH < 9) and carbonate (pH > 9) [44,45]. Fan et al. [44] discussed about the various resistances affecting the overall growth process of microalgae, starting from transfer of gaseous CO_2 to water and ending with utilization of CO_2 by microalgae. He also suggested the methods to overcome each resistance. Out of which highest resistance is at the site of reaction with microalgae. Chelf et al. [20] reported that mass transfer limitations could slow down the cell growth of microalgae. Area of contact and mixing will reduce the mass transfer resistance. Providing conducive environment such as desired concentration of CO_2, microalgae and dosage of light irradiance will reduce the resistance for biofixation reaction at the site of microalgae.

The ways of increasing surface area for mass transfer for absorption are directly bubbling or absorption in packed bed. In bubbling, the CO_2 laden air stream is broken into tiny bubbles by passing through a sparger in water. These tiny bubbles cause a wider area of contact between air and water. Many researchers have studied the effect of CO_2 by directly bubbling of the CO_2 in algal reactor [46–50]. The increase in CO_2 concentration in the air results in a proportional increase in dissolved CO_2 concentration in aqueous phase according to Henry's law [51]. Hill [45] showed that 10% CO_2 by volume in the gas phase results in a total dissolved CO_2 concentration of 3.5×10^{-3} M (150 mg/L) and is only 1.5×10^{-5} M (0.7 mg/L) for air containing 0.037% by volume CO_2. The disadvantage of bubbling CO_2 is more power consumption for operation and also causes algal cell damage.

Alternate method to supply CO_2 for microalgae growth is to use packed bed absorption column, admitting flue gas/air and water in counter current manner. However this also consumes more power to overcome the pressure drop offered by the bed.

To overcome these problems of high power consumption and cell damage in bubbling/packed bed, design to be made for providing large surface area to support high mass transfer rate and the microalgal growth. Exposing microalgal suspension as a thin layer to CO_2 is helpful to increase the mass transfer of CO_2 to water. Using thin layer culture technology, low utilization of CO_2 could be eliminated due to the efficient method of CO_2 supply. By thin layer technique the utilization of CO_2 rate by the microalgae is found to be greater than 60%, when compared to the utilization of the gas in the closed system [52]. Therefore it is evident that a*ny proper method of increasing the surface area per unit volume of water enhances the CO_2 mass transfer rate with less power consumption and without cell damage.*

Absorbed CO_2 should be available in water until all the CO_2 is consumed by microalgae. When the absorbed CO_2 is exposed to environment, the desorption occurs. Desorption rate of CO_2 to the environment is a function of (1) flowing air (wind) over that and (2) increasing water temperature. The desorption of CO_2 from the CO_2 absorbed water depends upon the partial pressure of CO_2 in air which is in contact with water, flow rate of that air and water temperature. Hence to overcome the problems of CO_2 loss into the atmosphere after being captured, a proper storage mechanism is essential to maximize the utilization of CO_2 for microalgae growth.

Absorption of CO_2 by chemical reaction can be used to stabilize the CO_2 as carbonates in water, the concentration of which should be equal to the uptake rate of CO_2 by microalgae. One such method is absorbing CO_2 in alkaline solution [53]. It increases the CO_2 removal efficiency in the packed tower by 5 fold at pH 12.2 compared to pH 8.9 [54]. The solubility of CO_2 increases, thus providing more CO_2 availability. As the solubility is very high, further desorption of CO_2 to atmosphere is reduced. Availability of CO_2 for microalgae growth is thus achieved, however it is again species limited. Doucha and Livansky [55] reported that formation of CO_2 from bicarbonate ions resulted in the better utilization rate of CO_2 in the bioreactor. Researchers reported that some species are able to utilize carbonate and also some in the form of bicarbonate [53–59]. Higher carbonic anhydrase activity aids for the conversion of carbonate to free more CO_2 to facilitate CO_2 assimilation. Species acclimatization to bicarbonate uptake helps in proper CO_2 utilization as well as mitigation strategy. Hence, a*ny method of storing absorbed CO_2 by chemical means and regeneration to release CO_2 for algal growth is the most effective.*

2.1.2. Fixation

The fixation of CO_2 means uptake of CO_2 by microalgae for its growth. One gram of dried microalgae biomass requires 1.65–1.83 g of CO_2 [60]. Carbon fixation will be increased only when the carbon dioxide residence time is increased in bioreactors [61]. Thus sufficient time should be provided in order to achieve higher fixation. Fixation rate depends on temperature and number of available photons required by microalgae. Since the fixation rate of CO_2 by microalgae is fixed for any given operating conditions, the absorption rate of CO_2 should be adjusted equal to that of fixation rate. The time for absorption of CO_2 from air/flue gas by water and time required for fixation of CO_2 should be more or less same. *Thus the photobioreactor should provide residence time for absorption of CO_2 matching with the fixation rate i.e., the growth rate of microalgae (Criteria 1).*

2.2. Light

Microalgae can utilize only the energy available in the wavelength range of 400–700 nm, represented by photosynthetically active radiation (PAR).45% of the energy at the earth's surface is PAR [62]. Photosynthesis occurs only due to the absorption of light energy. Light energy is represented in the terms of photon flux density (PFD) (μmol/m^2/s). Higher PFD will result in the photo damage and thus reduces the photosynthetic capacity [63]. Hence, photo acclimation is essential, unless cells will die in short time with exposure to sudden, great surge in light [64–66]. The introduction of a dark zone also reduces photo damage effect by avoiding long exposure to high PFDs and providing dark time for microalgae to repair photo induced damage [67]. Janssen et al. [46] have reported that light/dark cycles in the range of 10–100 s could have a considerable influence on the efficiency of light utilization. The dark period should be limited to about 20% of the cycle time to maintain a biomass yield on light energy as high as under continuous illumination of this PFD. The efficiency was found to decrease when longer darker periods, 50% of the cycle time, was applied [68]. The light dark cycle ratio also influences the productivity as well as the byproducts.

The photosynthetic rates are determined by average PFD to which the individual cells are exposed.

The interrelationships between growth rate and photosynthesis in outdoors are expressed in solar irradiance and temperature [69,70]. Similar effect also observed as the specific growth rate increases with the average scalar irradiance up to a certain value and then decreased [71]. Hu et al. [72] have reported the interrelationships of the output rate, photosynthetic efficiency and the range of optical cell density in *Spirulina platensis* as affected by incident light intensity and rate of mixing. Morita et al. [73,74] also observed that the availability of light limited photosynthetic productivity in their Photobioreactor.

Thus for a given PFD and reactor design, an optimum levels of microalgae population density should be maintained to achieve higher photosynthetic rate and means to be provided to expose all the cells equally to sunlight.

Csogor et al. [75] reported that the minimal quantum demand for the production of one molecule of oxygen and fixation of one

molecule of carbon was 15.9 and 17.3 photons, respectively. The minimal quantum demand for a carbon atom to be incorporated into biomass is 38.8 photons. The number of photons required is proportional to the microalgae concentration in water and the illuminated surface area per unit volume of reactor.

Increasing radiant flux of (6.0–32.3 mW) resulted in the increase in growth rate of 0.4–1.0 mg/L/h for unenriched air, whereas for 10% CO_2 enriched air it was 0.4–3.6 mg/L/h [76], implying that higher CO_2 could be taken up by microalgae in presence of higher radiant flux. Hence, proper utilization of solar light intensity available in India is a viable solution for high CO_2 fixation.

The depth of the algal reactor is limited due to the least availability of light at greater depths. Light transmission in clear water upto a depth of 15 cm is found to be satisfying the demand of microalgae. The greater the depth of the culture, the stronger is photo limitation and photo inhibition [77]. The light penetration is also affected by scattering due to algal particles.

The higher photosynthetic rate in bioreactor is achieved in minimum light path. The bioreactor permits cultivation of microalgae in a layer of only a few mm up to a harvesting density higher than 30 g (DW)/L [78–81]. This result indicates that as long as the water is spread to a wider area as a thin film, the absorption of photon at a given concentration of microalgae and wavelength would be excellent. The time required for absorbing the desired number of photons, thus depends upon the spread of water (thickness) and microalgae concentration.

Therefore for a given PFD, sufficient exposure time to supply required number of photons matching with the microalgae and CO_2 concentration. Optimum light/dark cycle ratio should be provided to achieve higher productivity by reducing photo damage effect (Criteria 2).

2.3. Optimum concentration of microalgae

At any concentration of CO_2, light and nutrients, the growth of microalgae undergoes lag, log, deceleration, stationary and death phases. Initial concentration of microalgae is an important parameter. To minimize the duration of the lag phase, cells should be adapted to the growth medium and similar environmental conditions before inoculation, cells should have been young and the inoculums size should be large (5–10% by volume). The age of the inoculum has a strong effect on the length of the lag phase. During exponential phase, cells can multiply rapidly and cell density increases exponentially with time.

Experimental data shows the growth of Scenedesmus at various time intervals shown in Fig 1. Table 1 lists the various operating conditions used in a batch reactor.

It is evident from Fig. 1, the Biomass concentration vs. time follows S shaped curve indicating all the phases of growth stage.

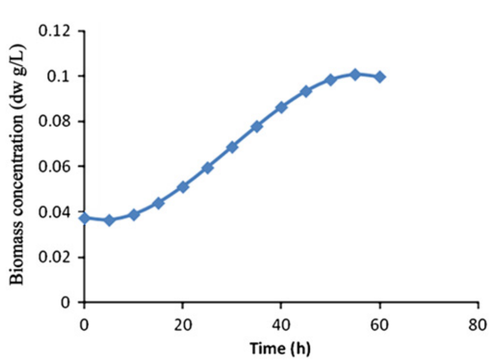

Fig. 1. Growth curve of *Scencdesmus sp* with time undergoes lag, log, deceleration and stationary phases of growth resembling s shaped growth curve.

Table 1
Operating conditions for batch study.

Species	*Scenedesmus sp*
Light	Sunlight
Volume of the reactor	70 L
Nutrients	N, P and K

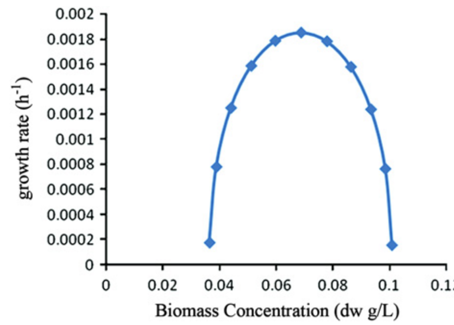

Fig. 2. Growth rate vs. concentration resembles the inverted parabola. The growth rate increases till 0.0018 and then decreases.

The rates of growth at various concentrations of microalgae were determined from the slope of the curve. Fig. 2 gives the rate vs. concentration data.

The shape of the curve (Fig. 2) is like an inverted parabola indicating an optimum concentration at which the rate is high. This behavior can be attributed similar to an autocatalytic reaction [82]. The rate of growth is directly related to cell concentration and cellular reproduction is the normal outcome of this reaction [83]. When the initial concentration of microalgae is less compared to light and CO_2 absorbed, the growth rate increases up to a point of optimum concentration. After which the continuous depletion of CO_2 and nutrient concentration, outweighs the benefit of having more microalgae and the rate of growth decreases with microalgae concentration. Similar observations have been reported that the population density must be maintained at its optimum i.e., the cell concentration which will result in the highest net yields [84,85]. By maintaining at the optimum population density, the rate of O_2 evolution per given PFD is higher as is the net output rate, indicating the highest efficiency in utilizing solar irradiance.

In a continuous process, an optimum concentration should be maintained by harvesting the excess microalgae formed above the optimum concentration to achieve the highest rate of microalgae growth thus reducing the size of the reactor for a given production rate (Criteria 3).

2.4. Nutrient

Low concentration of some nutrients may cause a long lag phase. Sufficient nutrient medium should be provided to sustain the maximum growth rate. *The sufficient nutrient level in the growth medium should be maintained by supplying an equal quantity of nutrient that is consumed by harvested algae (Criteria 4).*

3. Photobioreactors

An economically viable photobioreactor could be designed by incorporating the following features:

- Providing highest surface area/volume ratio
- Stabilizing absorbed CO_2
- Providing sufficient time for absorption of photons

- Maintaining optimum concentration of microalgae matching the highest rate
- Maintaining desired level of nutrients

The design and operation of some of the existing photobioreactors are discussed with reference to the above features. Despite the development of number of photobioreactors, only very few of them can effectively utilize solar energy for mass cultivation of microalgae. Photobioreactor development is perhaps, one of the major steps that should be undertaken for efficient mass cultivation of microalgae. The major challenges in the design of efficient photobioreactors are the means of providing large capacity to maximize the utilization of outdoor solar radiation, equal exposure of light to all cells, large volume with less land space, higher surface area to volume, high mass transfer rate to achieve higher productivity.

The most widely used photobioreactor designs are open raceway ponds, tubular photobioreactor and flat plate bioreactor.

Raceway ponds are the most widely used and economical one for the large scale cultivation. Cultivation of microalgae in open ponds has been extensively studied in the past few years [86–88]. One of the major advantages of open ponds is that they are easier to construct and operate than most closed systems. Solar light can be used as source for light. The depth is limited due to light penetration and scattering of light by particles of microalgae. The productivity is limited due to poor utilization of light and higher prospect of contamination. Hence, this system is limited to only few species. Another major drawback is large land space requirement for cultivation. Other limitations in mass cultivation include evaporation losses, high temperature, high CO_2 desorption due to wind, poor mass transfer efficiency and inefficient mixing. Thus mass culturing in open pond results in less photosynthetic effect. The maintenance of low microalgae concentration, improper exposure to light leads to lower carbon fixation. Beker [89] reported that only 13–20% of supplied CO_2 was absorbed in raceway ponds. Higher utilization rate of 70% was observed in raceway ponds by admitting 0.1–0.2 vol% CO_2 [55] but increases the land space requirement. Flue gas emitted from the thermal power plant has 15% CO_2. Diluting this to such a lower concentration will involve handling of large volume of flue gas and increases land space requirement. Recently Putt et al. [90] reported that integration of carbonation column in the pond increases mass transfer efficiency by 83%. Anyhow these modifications have to be analyzed further in detail to achieve higher productivity in an economical and easy operation.

Tubular reactor is one of the most suitable types for outdoor mass cultures. Glass or plastic tubes are the materials used for construction of reactor. Horizontal/serpentine [91,92], vertical [93], near horizontal [94], conical [95], inclined [96,97] photobioreactor designs are so far reported. Increased surface area is the great advantage of the system. But, O_2 accumulation inside the reactor leads to the poor productivity [91–99]. Also, photo inhibition is very commonly reported in outdoor tubular photobioreactors [100]. Efficient light distribution to the cells can be achieved by improving the mixing system in the tubes [101–103]. Culture density maintained inside the closed system is 5–6 times higher than that of the raceway ponds [104]. Surface area to volume ratio decreases with increase in diameter for scaling up and results in lesser productivity due to mutual shading, insufficient light and poor mass transfer rates. However scaling up is only achieved by multiple number of tubes. They can be equipped with thermostat to maintain the desired culture temperature, but are very expensive and difficult to operate. Hence, high temperature, O_2 accumulation, photo inhibition, CO_2 sparging, land requirement and more power consumption are the problems with the tubular reactor.

Flat-plate photobioreactors have received much attention for cultivation of photosynthetic microorganisms due to their large illumination surface area and smaller light path. The smaller light path enhances the higher photosynthetic efficiencies. Hu et al. [104] reported higher productivity of 80 g/L in flat plate reactors. Accumulation of dissolved oxygen concentrations in flat-plate photobioreactors is relatively low compared to horizontal tubular photobioreactors. High density cultures are easily maintained and achieved due to smaller path length. Higher productivity is very much suitable for mass cultures of microalgae. This reduces harvesting cost. The smaller path length provides the sufficient time of exposure thus this design results in high productivity [105–107]. The advantages are due to the highest surface area to volume ratio. However, scaling up is limited with the large requirement of land area.

In general, one MW thermal power plant would produce 8760,000 Units. Considering an average of 1 kg of CO_2 emitted per unit of electricity production. Thus 8760,000 kg of CO_2 emitted from 1 MW/yr. The carbon uptake rate by microalgae is 1.83 g by 1 g algal dry biomass [108]. Thus 4786.88 t of algal biomass/ MW could be formed or 13.11 t microalgae/MW/ day. The maximum algal productivity per square meter is 30 g/day. The land requirement will be approximately 0.44 km^2/MW. The calculation matches with the data of Grobbelaar et al., [109]. The land requirement is so high and thus operation & maintenance of the system is also too difficult. It is thus necessary to have an efficient reactor design with highest productivity which will reduce the size and make its operation economical. The major drawback of the algae cultivation practice is the inadequacy to maintain and operate large cultivation systems and this need to be examined, especially for point CO_2 source like a thermal power station. The proposed design criteria thus well suit for the fixation of CO_2 from major point source like a thermal power station.

Similarly, the theoretical photosynthetic efficiency for microalgae growth is only 9% and in practice it is still lower. India is well renowned for the solar radiation availability. The average PAR intensity will vary depending upon the climatic conditions from 500 $\mu mol/m^2/s$ to 4500 $\mu mol/m^2/s$. An average PAR intensity of 1500 $\mu mol/m^2/s$ is available in India. Considering 10% of this energy, then 150 $\mu mol/m^2/s$ is used for carbon fixation. If approximately 40 photons [75] are required for 1 mol of CO_2, then 3.75 $mol/m^2/s$ (165 g of $CO_2/m^2/s$) of CO_2 could be fixed considering only photon availability. If 5 h of sunshine is available then the requirement of area is only 8 m^2 for complete absorption of CO_2 produced per MW. This indicates the requirement of an efficient bio-reactor to provide necessary conditions and suitable species that will have an equivalent biofixation rate as that of photon supply rate. The available systems fail to provide the necessary conditions for photobioreactor and the suggested criteria of design would prove useful.

4. Discussion

Sequestration of carbon dioxide is the best solution available for controlling global warming via CO_2 recycling through conversion to useful products including fuels. Sequestration using microalgae is considered to be more efficient than higher plants. This process involves fixation of carbon dioxide and photons from light by these microalgae in presence of supporting nutrients.

Performance analysis of Bio-fixation of CO_2 is based on the photobioreactor designed on the basis of the proposed design criteria. None of the widely used present day Photobioreactor satisfy all the proposed design criteria.

Criteria 1. Maximum absorption of CO_2 to be achieved. This is not satisfied, since carbon dioxide availability is by

bubbling of CO_2 in all the existing types of bioreactors.

Criteria 2. Maximum absorption of light and uniform exposure of light to all cells. This is not satisfied because of improper illumination that may be caused by excessive growth of algae and inadequate time provided for absorption of photons which leads to decrease in photosynthetic efficiency and algal productivity.

Criteria 3. Maintaining an optimum concentration of algae to achieve maximum growth rate while continuously harvesting the excess algae. In all the existing types of photobioreactors, concentration of algal productivity is maintained with respect to permitting maximized light penetration but rarely for achieving maximum growth rate.

Criteria 4. Maintaining nutrient concentration at a constant level. The loss of nutrients due to harvesting has to be made up to maintain nutrients concentration at a constant level. In practice the trend is to maintain nutrient concentration in the reactor with an expectation to get maximum biomass while it should be done in consonance with the harvesting rate.

Ultimate requirement to make the bio sequestration economical are selecting suitable species with high growth rate, high CO_2 fixation ability, low contamination risk, low operation cost, be easy to harvest and rich in valuable components in their biomass [110,111,]. The absence of understanding the growth mechanism makes the scaling up of these reactors unreliable. These can be achieved only when the proper design of photobioreactor is developed. It is evident from the review on the performance of existing bioreactor that maintaining optimum concentration to match the highest rate providing highest surface area to volume ratio and sufficient exposure time for light are very essential for the maximum productivity and none of the above reactors is designed taking these factors into account.

5. Summary and conclusion

Energy generation activities mostly lead to CO_2 emission resulting in global warming. Mitigation and sequestration of CO_2 are essential to contain ever increasing CO_2 concentration in atmosphere. Several costly attempts are available for improving the efficiency of energy activities to reduce CO_2 emission. However sequestration of CO_2 is the only way of overcoming global warming. Physical, chemical and biological methods of sequestration of CO_2 are being practiced. Physical methods include capturing, storing and utilizing CO_2 for chemical industries. Chemical methods include absorption by monoethanol amine scrubbing and other base solutions. Biological methods include photosynthesis of plants and microalgae. Photosynthesis of microalgae appears to be attractive over that of plants. The microalgae growth kinetics indicates that the rate increases and decreases with the concentration of microalgae and highest at an optimum concentration. The mechanism of photosynthesis of algae involves providing highest spreading area to volume ratio, stabilizing the CO_2, maintaining optimum concentration corresponding to highest growth rate and maintaining nutrient concentration. Ensuring the above criteria into the design of photobioreactor will be helpful to achieve an economical photobioreactor system.

Acknowledgement

We sincerely thank Department of Science and Technology (DST) for giving us an opportunity to work on the most important research area on microalgae for CO_2 mitigation (DST/IS-STAC/CO2-SR-12/07).

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